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IMPORTANCE OF SPECTRUM FOR RATING HAZARD: THEORETICAL BASIS

G. Richard Price

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The theoretical basis for the use of spectrum in rating hazard is well established for sound intensities most often encountered in the workplace. The frequency-selective transmission characteristics of the conductive mechanisms of the external and middle ears, coupled with the generally broad and gently sloped spectra of noise in the workplace, promote energy transmission in the midrange so that some measure of energy there should do well at ranking hazard. However, at sound pressures above 130 dB, often exceeded by impulsive sounds such as gunfire, the picture is much more complex. Conductive non-linearities in the middle ear can act to reduce the energy transmitted to the cochlea, protecting the ear and allowing it to resist damage. At the same time, however, the mechanisms of loss operating within the cochlea become very sensitive to amplitude so that relatively small quantities of energy can do permanent damage. These mechanisms are not well characterized in the frequency domain; consequently, spectrum is likely to have marginal utility in rating hazard for really intense sounds.

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U.S. ARMY HUMAN ENGINEERING LABORATORY

Aberdeen Proving Ground, Maryland

CHAPTER 31

Importance of Spectrum for Rating Hazard: Theoretical Basis

G. RICHARD PRICE

Raising the question of the importance of spectrum in rating auditory hazard may at first glance seem like the resurrection of an issue long since put to rest. More than a century ago, Helmholtz would have been comfortable with the idea that the ear is spectrally tuned; contemporary textbooks introduce students to the familiar U-shape of the audiogram, which clearly demonstrates that the human ear is most sensitive in the mid-frequencies. Furthermore, regulatory bodies in the governments of many countries have accepted the idea of using A-weighting in the assessment of auditory hazard, testimony to the notion that spectrum is a useful concept in rating hazard.

On the other hand, scientific interest in spectrum and hazard continues (see for example Decory and Dancer; Hamernik and Patterson; Hetu et al; Liang; and Smoorenburg). For industrial noises, there is the question of whether a simple A-weighted measure of energy is adequate to rate hazard, given that it "explains" so little of the variance in the data. And for really intense sounds, like gunfire, only France uses a frequency-weighted measure of hazard (Ministry of Defense, 1982a), whereas the rest of the world's impulse noise criteria depend on measures of peak pressure and duration (CHABA, 1968; Cheng et al, 1987; Ministry of Defense, 1982a,b; Pfander, 1975). At the same time, research with intense impulsive sounds seems to indicate that spectrum has a major effect on susceptibility (Dancer et al, 1985; Price, 1986). The issue of the importance and use of spectrum in rating noise hazard is in fact far from settled.

The major proposition of this chapter is that approaching hazard assessment in spectral terms may be useful. Calculation of spectral information can be thought of as a sort of mathematical model of important processes associated with hazard. Insofar as a model matches the behavior of the system being described, the application of the model should be simple. If, on the other hand, the model behaves differently than the system in important ways, then the application of the model should be constrained to allow for such mismatches. Therefore, I examine the relationship between the calculated spectrum of a sound and the prediction of the ear's response to it in order to identify the range of conditions in which spectral information might be useful and to identify those areas in which the spectrum may not be related to the ear's behavior and thus not be a useful predictor of hazard.

This chapter is focused on developing the relationship between spectral measures of sound and the application of those measures to the assessment of noise hazard. I make no pretense of developing the mathematical basis for spectral analysis or of preparing a guide to the practical application of spectral analysis to specific noise measurements. This chapter should promote insight into the problems associated with the application of spectral concepts to the interpretation of the effect of intense sound on the ear and establish some range of conditions over which spectral analysis might be useful.

A Spectral Model

Most of us have an intuitive, albeit imprecise, appreciation of spectrum, perhaps because of the association between the spectrum of a sound and the auditory experience of pitch and timbre. Spectrum can be defined precisely in the mathematical realm by means of the Fourier integral; but as a formula it remains something of an abstraction. As an aid in

thinking about spectrum, a mechanical analogy may be useful, at least for those of us who find mechanical analogies intellectually congenial. An image put forward by Trent (1960) and further developed by Kalb (1982) is that of a bar from which are suspended undamped, tuned oscillators, represented in Figure 31-1 as a graded series of weights suspended from springs. If the bar moves so that its velocity is proportional to the instantaneous pressure during an analysis period, then the oscillator amplitudes at the end of the analysis period match the components of the pressure spectral density. At this point we can see the "spectrum" of the noise in the amplitude of each of the oscillators (the size of the envelope drawn at the limit of the balls' travel in Fig. 31-1). But this insight has been gained at a price. Specifically, we have lost track of the instantaneous events that resulted in the final pattern we see when the analysis interval is ended. Patterns of vibration could have built up and canceled; but the spectrum shows only the final result. For some purposes this loss of temporal detail inherent in moving from the time domain into the frequency domain may be of no consequence; but if, for instance, the instantaneous displacements of the oscillators were an issue, the spectrum might not reveal essential information or it could distort important details. Succeeding sections of this chapter identify situations in which these considerations might be relative to predicting hazard from intense sounds.

Utility of Spectrum

The Problem of Linearity and Continuity

In applying spectral analysis to a system, we implicitly assume that the system is linear. With a linear system, a transfer function is a powerful way to describe the behavior of the system as it responds to complex time-varying stimulation. On the other hand, nonlinearities or discontinuities can lead to gross misrepresentations. This is a major problem with the application of spectral analysis to the ear in two areas. Specifically, the conductive path becomes nonlinear for large displacements (Price, 1974; Price and Kalb, 1986) and, perhaps more debatable, the loss mechanisms operating within the cochlea go through a change of mode, also at high levels (Price, 1981). Much might be debated about the specifics of these points, but their general impact will be apparent in appropriate sections of the discussion.

Range of Application

Where might we expect spectrum to be a useful concept, and over what range of conditions might we expect it to provide useful insights?

Conductive Path

The most obvious point is that the mechanisms that conduct sound to the cochlea are spectrally tuned and therefore play a major role in determining cochlear input. A great deal of research and time has been invested over the last 50 years in determining the acoustic properties of mammalian external and middle ears. As a result, it was determined that they function collectively to transmit energy to the cochlea best in the mid-range of frequencies and to be essentially linear with respect to amplitude over essentially the entire normal physiologic range. The middle ear transmits most efficiently at its resonant frequency, near 1.0 kHz for the human. At frequencies below resonance, the efficiency of transmission falls off primarily because structures are not sufficiently compliant; at frequencies above resonance, sensitivity declines primarily because the structures are too massive. The external ear acts as a resonator and extends the region of maximum sensitivity upward about two octaves, so that the ear is an efficient collector of energy for perhaps a 3- or 4-octave range; but it rapidly becomes less sensitive at both higher and lower frequencies. This pattern of sensitivity is reflected in psychoacoustic functions such as the minimum audible pressure and equal loudness contours, from which the A-weighting curve is derived. The theoretical basis for the spectral tuning of the ear (at least from the free field to the stapes) is thus well established, at least for the range of intensities for which the middle ear is linear.

An additional element in the conductive chain, the middle-ear muscle system, also tends to reinforce the same pattern of stimulation. The middle-ear muscles are active during noise exposures, the pattern of action varying over time in a complex fashion; but they have long been known to have their greatest attenuating effect on the low frequencies and to leave the mid-range much less affected (Wiggers, 1937). Therefore, the middle-ear muscle system acts to further sharpen the tuning of

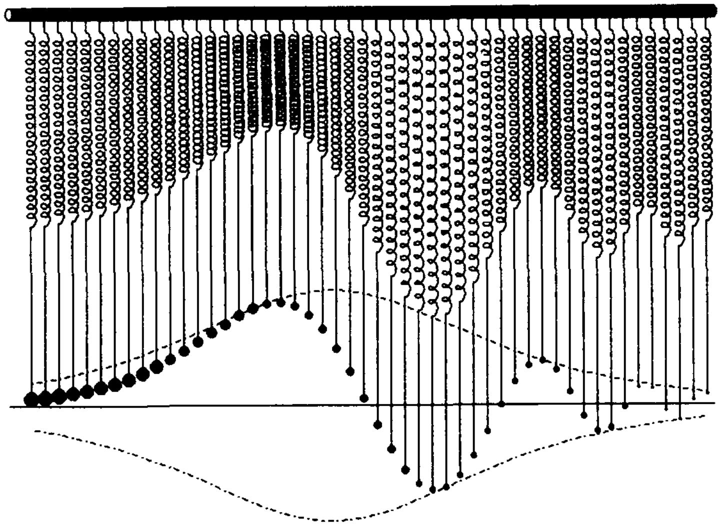

Figure 31-1 Model spectral analyzer at the end of the analysis interval showing the pattern of response in the graded series of oscillators.

the ear by selectively attenuating the sounds below the resonant frequency.

Cochlea

Actual damage to the ear, however, is primarily a function of changes inside the cochlea. How do spectral concepts fit at that level? Given that the intracochlear structures are uniformly graded from base to apex with no apparent discontinuities, it is reasonable to expect that when the auditory system is stimulated with loud sounds, the effect on the inner ear will reflect the spectral shaping of the middle and external ears. And this is essentially the case. Kryter et al (1966) plotted the ear's susceptibility to continuous and intermittent noise, incorporating a great deal of noise research in which ears had been exposed to bands of noises at different frequencies. Their plot of tolerable exposures specifically took spectrum into account by allowing the lowest exposure to bands of noise in the mid-range, where the ear is tuned best, and progressively more exposure at higher and lower frequencies, where the ear is tuned less well. A simpler and more popular approach to the same end has of course been the use of A-weighting in the assessment of auditory hazard.

Another way of looking at the same phenomenon is to consider the pattern of loss when an ear is exposed to intense sounds in the workplace. One of the early audiologic observations was of the "4,096 cycle notch" in the audiogram, now commonly taken as a sign of noise-induced hearing loss. Two circumstances act to produce this effect. In essence, the spectral tuning of the ear is relatively sharp compared to the spectra of the noises commonly found in the workplace. The steepest spectral slopes found in real settings are about ± 6 dB per octave, but the tuning of the ear is very much sharper than that. Therefore, the middle of the cochlea customarily receives the maximum stimulation. This combination of conditions forms the physical basis for explaining the common finding of the greatest damage occurring in the midrange.

Loss Mechanisms Within the Cochlea

The discussion thus far has not specifically addressed the fit of spectral information to specific loss mechanisms within the cochlea. At this point the discussion becomes highly speculative because, despite excellent research on the mechanisms of loss operating within the cochlea, we still know relatively little about the specific effects of intense stimulation on intracochlear structures, the recovery processes, etc. With that caveat, the following speculations are offered.

It is reasonable to suppose that for noises that are commonly present in the workplace, the loss mechanism might be thought of as extreme metabolic demand on the cochlea. In that case, some quantity like energy might do reasonably well in representing the stress. In fact, Ward et al (1983) have shown that, for the chinchilla, the percentage of outer hair cells destroyed by continuous exposure to a 2-octave band of noise (700 to 2,800 Hz) is a linear function of the square root of the energy in the exposure, as long as sound pressures are below 114 dB. Given that the chin-

chilla is usually regarded as somewhat more susceptible than the human being, it is reasonable to suppose that for sound pressures up to about 115 dB, some measure of energy in the midrange would be a good way of characterizing hazard for the human ear.

It should be recognized that whereas spectrum plays a role in determining hazard, it is by no means the *only* determinant of the hazard represented by a sound. For example, there is a great deal of evidence that the temporal pattern of the presentation, previous exposure history, presence of ototraumatic agents, and individual differences in susceptibility all affect the amount of loss. Spectrum, as important as it may be, is only one issue among many.

Practical Application

Calculating the Spectrum

When we examine the practical details of calculating spectra, then additional questions arise. In theory, the analysis interval is infinitely long, and the displacements of our infinite number of undamped oscillators could grow forever. However, in the modern world of digital frequency analysis, the analysis interval is finite and there are a limited number of oscillators (the analyzer has only so much memory). These practical issues influence the number and spacing of the bumps and dips in the spectral display, which as a result may or may not match the behavior of the ear. Consider our imaginary frequency analyzer. We could suspend 19,981 oscillators tuned at 1-Hz intervals from 20 Hz to 20 kHz along the bar, or we could place 30 of them at ⅓-octave intervals, or we might put 10 of them at 1-octave intervals. All three approaches are commonly used in spectral analysis. However, the critical question is: which of these three "displays" would be expected to match just what structures in the ear? Would other analysis intervals or frequency spacings or both do better? Does this analysis work at all sound pressure levels, or does the behavior of the ear change as a function of level? Unraveling these issues is not a simple matter.

Interpreting the Spectrum

With modern technology, spectral analysis can be performed with deceptive ease. In its most elemental form, a microphone samples pressure in the free field and its output is fed into a spectrum analyzer. Shortly thereafter one is faced with the problem of interpreting an intriguing series of bumps and dips on a display that typically portrays frequency along the horizontal axis (usually a linear scale) and some measure of spectral amplitude, often on a logarithmic scale, on the vertical axis. Given an interest in the effect of intense sound on hearing and knowing that the cochlea can be characterized as a frequency analyzer, it is tempting to visualize the horizontal axis of the spectral display as an unrolled cochlea and the vertical axis as an analog of the stimulation received by the various sections of the basilar membrane.

And why not interpret the spectral plot in such a fashion? Several transformations would make sense if the spectral plot were to be conformal with the cochlea. Given that the waveform analyzed was a free-field sound pressure, it would be necessary to account for the transformations of the external and middle ears to arrive at an estimate of the actual input to the cochlea. In response to sound pressures up to 120 or 130 dB, the middle and external ears are known to be essentially linear and the transfer functions are known; hence, for sound pressures below these levels such a transformation would accurately indicate the spectrum at the stapes.

The second transformation that moves us from input at the stapes to activity on the basilar membrane is more tenuous. What should the horizontal axis show or, in terms of our model, how many oscillators should be on the bar and how should they be spaced? Within the cochlea, frequencies array themselves along the basilar membrane in an essentially logarithmic fashion; but spectra are often calculated for 1-Hz bandwidths or ⅓-octave bandwidths. The problem of finding conformality between the calculated spectrum and the ear is not trivial, and the choice is somewhat arbitrary. The 1-Hz bands provide greater resolution (more bumps and dips), and ⅓-octave bands are reasonably close to critical bands or approximately constant distances along the basilar membrane. The important issue is how our choice relates to the behavior of the ear. If we think in terms of the distribution and absorption of energy in the cochlea, then it is reasonable to argue that something like a ⅓-octave integration is analogous to what actually happens in the ear. Of course, in the ear the ⅓-octave bands are not fixed or even exactly ⅓-octave wide, but the general logarithmic "compression" of energy at higher frequencies is paralleled.

But having made all the right choices, just

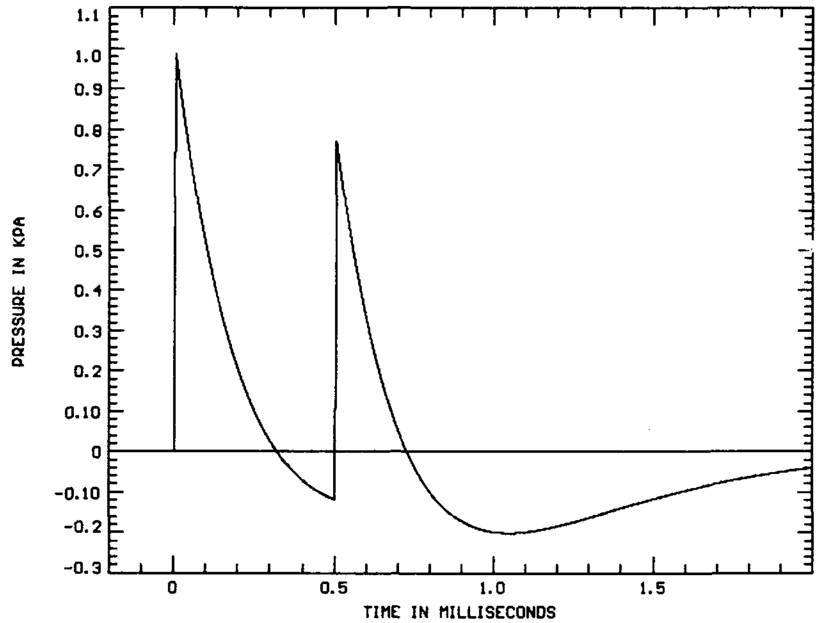

Figure 31-2 Friedlander waveforms simulating a rifle impulse and its ground reflection.

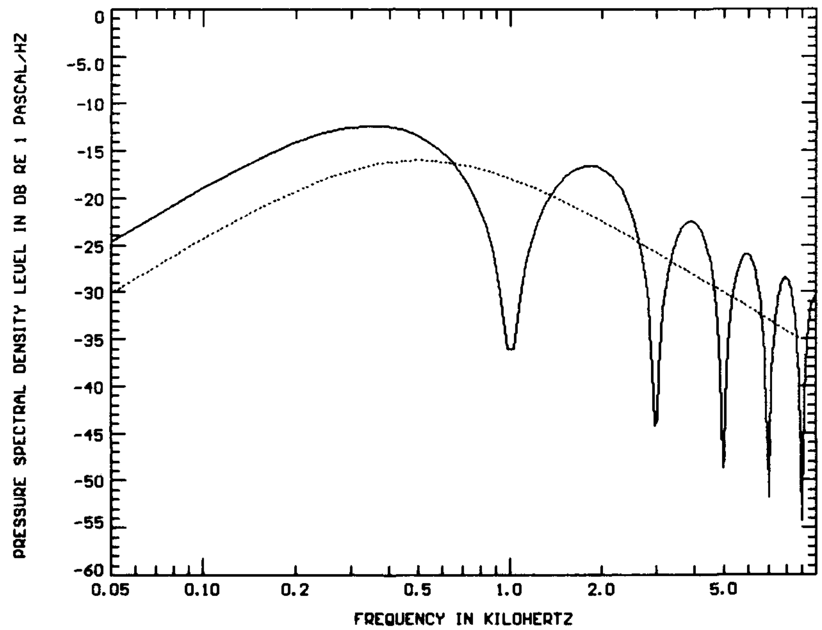

Figure 31-3 Spectra of the Friedlander waveforms in Figure 31-2. The dotted spectrum is for one of the impulses taken alone; the solid spectrum is for the two impulses combined.

how should we view those bumps and dips in the spectrum? The specific form the spectrum takes is a function of many elements that may or may not relate to specific events in the ear. Consider, for instance, the problem in Figure 31-2. A weapon's impulse (simulated by a Friedlander waveform) is almost always accompanied by a reflected impulse from the ground. If the analysis interval includes only the directly transmitted impulse or just the reflection from the ground (here taken to be a relatively good reflector), the two spectra would each be like that shown as the dotted line in Figure 31-3. The spectrum rises

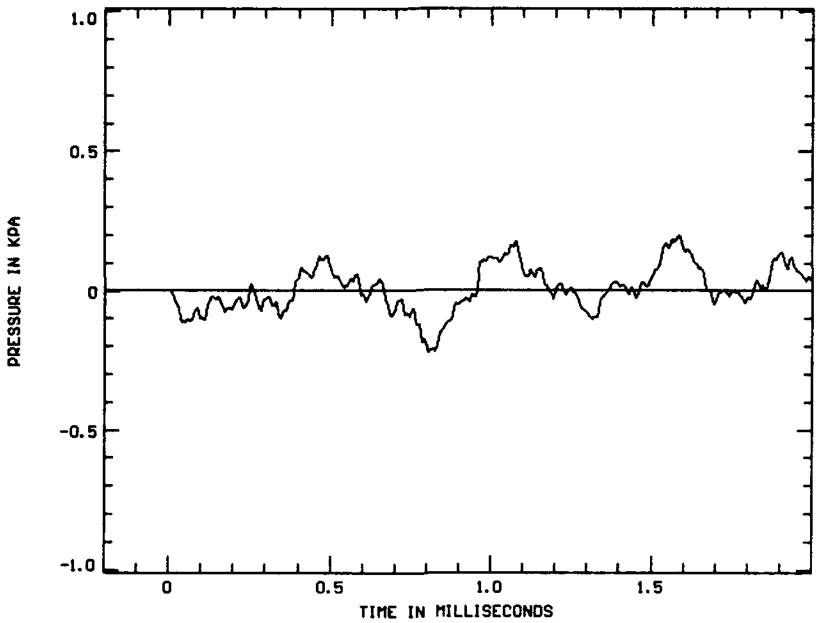

Figure 31-4 Pressure history of an impulse that has the same amplitude spectrum as the Friedlander waveform in Figure 31-3 (dotted line) but with a differing phase spectrum.

smoothly to a peak at 500 Hz and declines smoothly thereafter. But suppose the analysis interval includes *both* the direct and reflected impulses. Then the spectrum appears as the solid line in Figure 31-3. In terms of our ball and spring model, what we are seeing are patterns of constructive and destructive interference that exist in the oscillators at the end of the analysis interval. The low-frequency portion of the spectrum is now higher, which makes sense because there were two impulses, each carrying energy. However, there are now prominent peaks and dips at intervals. The specific pattern of bumps and dips is a function of the temporal spacing between the impulses and their relative sizes. Should the dips be interpreted as indicating relatively quiescent sections of the basilar membrane, or should the peaks be thought of as sections of the basilar membrane receiving maximum excitations? At this point the issue of conformality between the ear and the spectral analysis is apparent. The ear is not a series of lossless oscillators, as is our spectrum analyzer; consequently the analogy between the spectrum and activity within the ear breaks down. Patterns of interference and reinforcement would not be expected to develop within the cochlea for these impulses because in effect they would not be present simultaneously at the oscillator locations.

A variation on this same theme can be seen in Figure 31-4. The waveform in Figure 31-4 and a single Friedlander waveform like the one in Figure 31-3 (without the reflected impulse) are related to each other in an interesting way. Namely, their spectra are identical (the dotted spectrum in Fig. 31-3); but their pressure histories look very different because the phase relationships of their spectral components differ. Thus, two very different pressure histories in the time domain can have identical magnitudes in the frequency domain. If such impulses were to drive the ear, the specific temporal pattern of displacements within the cochlea would generally parallel their pressure histories, the first one having a quick large oscillation or two and the second having many much-smaller oscillations over a longer time.

So in the end, how should the bumps and dips be interpreted? Given that the phase information is not available, we can only guess at the temporal pattern of response. Even though we may be confident that the ear may have been exposed to the total energy represented by the spectrum, we cannot assert, in the case posed in Figure 31-2, that within the cochlea a particular place oscillated appreciably more or less than some other place, matching the bumps and dips in the spectrum. From these illustrations, it is apparent that in the absence of phase information, which would allow examination of the data in the time domain, extreme restraint should be used in interpreting frequency domain data. A

final comment on a more positive note: In a general sense, spectrum does indicate energy in different frequency regions, and over the long term in the workplace, the bumps and dips will average out and the spectrum may still retain its utility as a predictor of hazard.

Changes at High Intensities

As the intensity of stimulation rises above 130 dB, as it often does for impulse and impact sounds, additional complexities arise in the calculation, interpretation, and application of the spectrum. Several lines of inquiry are developing a picture of an intricate interplay of loss mechanisms and conductive nonlinearities at high sound pressure levels, which we will attempt to put in a conceptual framework.

To assist in maintaining a frame of reference for relative intensities, it may be worth noting that peak pressures of industrial impulses, cap guns, and even cordless telephones, often rise above 130 dB; small arms (pistols, rifles, shotguns) produce impulses with peak pressures of about 150 to 160 dB, and large-caliber weapons and shoulder-fired rockets can produce levels of nearly 190 dB. Sound pressures well above 130 dB are not at all rare in modern life.

I have argued that at very high sound pressure levels the middle ear becomes nonlinear with respect to amplitude, and the mechanism or mechanisms of loss within the cochlea also undergo a change. In both cases, instantaneous displacement of the structures is hypothesized to be critical; hence there is a fundamental analytical question as to whether a frequency domain analysis (spectrum) is an adequate descriptor of a time domain problem (mechanical stress).

A few calculations will demonstrate the nature of the problem. In the illustrations that follow, the figures are largely the result of calculations done with an integrated mathematical model of the ear that I have been developing with my colleagues at our laboratory (Kalb and Price, 1987; Price and Kalb, 1990). Input to the model is free-field sound pressure, and the model carries energy through the full transmission path to the stapes and ends by calculating hazard within the cochlea. Unfortunately, a full discussion of this model's development is beyond the scope of this chapter. However, the reader may be reassured to know that the model's structure parallels the ear's physiology, and that the external and middle ear sections closely reproduce the transfer functions and impedances that have been measured in real ears. The calculations reported here are made with values appropriate to the cat ear.

Nonlinearities in the Middle Ear

A nonlinearity in the middle ear implies that at some combination of frequency and intensity spectral calculations of energy in the free field will correlate poorly with cochlear input. Therefore it is important to establish the amplitudes and frequencies for which such an error becomes an issue. Various parts of the middle ear could impose a displacement limit; however, some have argued that on anatomic grounds it seems probable that the annular ligament of the stapes would be likely to pose an absolute limit to displacement of about 40 to 50 μm peak to peak (Price, 1974; Price and Kalb, 1986). At any rate, the model embodies this displacement limitation, and it has been used to calculate the level for Friedlander waveforms and tone pips at which the nonlinearity would have affected their amplitudes by 3 dB. The results are shown in Figure 31-5 for both the tone pips and Friedlander waveforms. For the Friedlander waveforms the clipping becomes significant at just over 140 dB for low-frequency impulses, and the clipping occurs at progressively higher levels as the waveforms get shorter (less low-frequency energy). Tone pips, on the other hand, are peak-limited in a pattern that roughly parallels the transfer function for the external and middle ears, which is what one might expect. Clipping becomes significant for them in the upper 140s for low-frequency tones and in the upper 130s where the ear is tuned best. The specific levels would of course be different for different species; but middle-ear nonlinearity is a major influence in high-level stimulation.

A middle-ear clipping nonlinearity would imply that an exposure would have less effect than expected when the middle-ear displacements rose to such amplitude that the nonlinearity was encountered. A pattern consistent with this idea can be seen in data from the chinchilla. When chinchillas were exposed to 100 impulses at 1.4 kHz spectral peak and at peak SPLs between 131 and 139 dB, losses grew rapidly as sound pressure increased, about 7 dB of threshold shift for every decibel of increase in peak pressure (Patterson et al, 1986). This is a spectral region in which the chinchilla is sensitive, and although we have

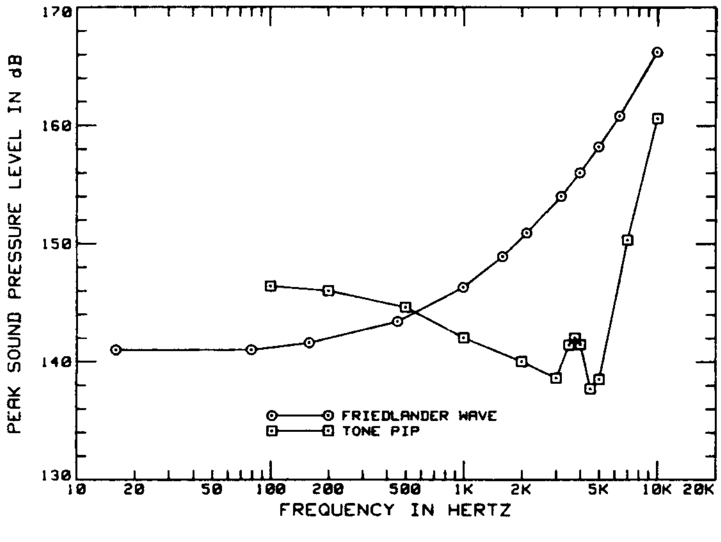

Figure 31-5 Free-field sound pressures at which a mathematical model of the ear (see Kalb and Price, 1987) indicates that Friedlander waveforms and tone pips would experience a 3-dB clipping effect.

no specific data, it seems likely that their middle-ear displacements would not be highly nonlinear at these levels. On the other hand, when chinchillas were exposed to impulses with peak pressures between 150 and 160 dB and spectral peaks below 125 Hz, the growth of threshold shift to 100 impulses had a slope of about 3.0 dB for every decibel of increase in peak pressure (Hamernik et al, 1990). This reduced slope is consistent with the possibility of amplitude limitation at the stapes. Or consider data from an experiment in which cat ears were exposed to one round from a recoilless rifle fired within a room (Price, 1978). The peak pressure was 186 dB, and the energy in the exposure was about 36 kJ per square meter (equivalent to 10 or *more* years of exposure in the workplace), but the average permanent losses were only about 10 dB. These data from the chinchilla and cat are not definitive; but they are consistent with a middle ear that transmits less well at high levels.

Calculations with the mathematical model of the ear have suggested a variation on the same mechanism that could have a major effect on the transmission of energy into the cochlea (Price and Kalb, 1990). At least part of the reason for the smaller-than-expected losses from intense, low-frequency impulses, such as those produced by large-caliber weapons, lies in the modulation of cochlear input by clipping of the stapes. Sommer and Nixon (1973) conducted an experiment that was particularly well suited to demonstrating this effect. They were trying to test auditory hazard from different acoustic components of air bag deployment in an automobile. They simulated air bag deployment by combining a hiss, a 153-dB band of noise at about 1.0 kHz (noise of the bag filling), with a relatively long positive pressure pulse (165 dB peak, simulating the pressure in the car as the bag filled). The low-frequency pulse produced no threshold shift by itself, and the hiss produced a modest threshold shift by itself; but together, they produced *less* threshold shift than the hiss by itself. By means of the mathematical model, the basis for this effect can be discerned. In the lower panel of Figure 31-6 we see the free-field pressure history of a simulated air-bag-deployment pulse consisting of a trapezoidal pedestal (160 dB peak pressure) combined with a tone pip (160 dB peak to peak). In the upper panel we see the calculated stapes response to the combined pulses. The lower-frequency impulse clearly modulates the cochlear input to the tone pip, reducing it by approximately 20 dB. Calculations with the mathematical model and with real weapons impulses suggest that exactly the same thing happens with them as well. In Figure 31-7 note, for example, the calculated stapes displacement in the lower panel in response to the impulse in the upper panel. The clipping is apparent. During the initial 4 or 5 ms the pressure is relatively high, but the stapes is relatively immobile and is held in position by the high pressure. However, stapes displacements are large whenever the waveform passes through ambient pressure. The relatively small pressure oscillations present in the last 10 ms of the period produce surprisingly large stapes displacements.

Upon consideration of the foregoing arguments we can conclude that there is a reasonable physical basis for the ear to be surprisingly resistant to damage at very high levels.

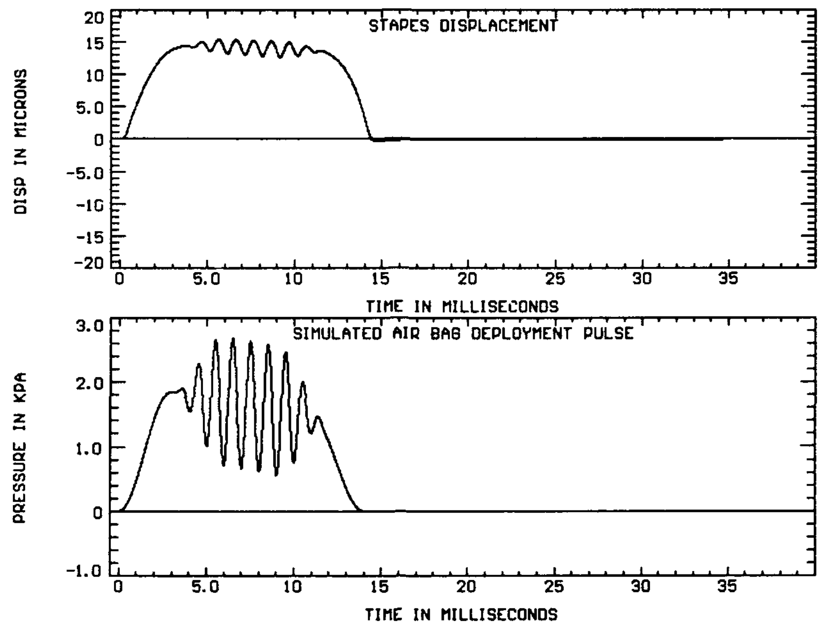

Figure 31-6 Demonstration of co-modulation at the stapes. The lower panel shows the pressure history of a simulated air-bag-deployment pulse. The upper panel shows the mathematical ear model's calculation of stapes displacement response, showing modulation of the tone pip by the lower-frequency pedestal.

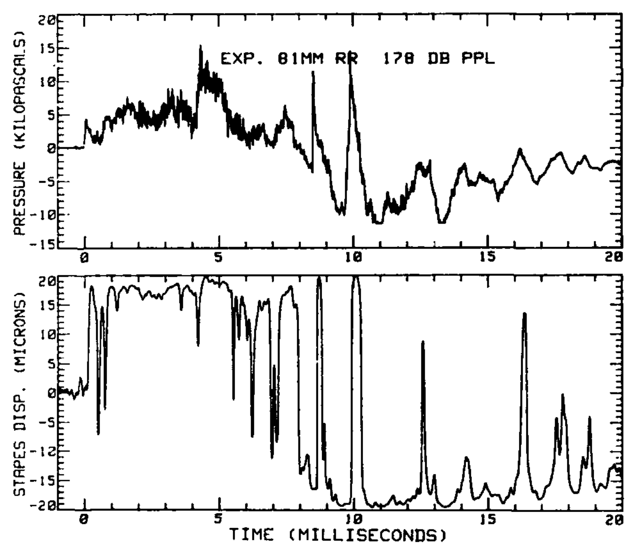

Figure 31-7 Pressure history of an experimental recoilless rifle (upper panel) and the calculated stapes displacement to the impulse (bottom panel).

A Change in the Mechanism of Loss

An additional complexity at high levels is that hazard to the ear rather suddenly becomes very sensitive to level (Patterson et al, 1986; Price, 1981; Ward, 1988). A change of intensity of about 10 dB in level for a given number of impulses could result in an increase ranging from no measurable loss to a total loss of hair cells. Presumably this is a result of the basic loss mechanism becoming some form of mechanical stress within the cochlea. The level at which this change occurs is important because it affects the range over which energy calculations at different spectral locations might be useful as a means of assessing hazard. Perhaps the most complete data pertaining to this issue are now available for the chinchilla ear. Data from Patterson et al (1986) are available for chinchillas exposed to impulses (a damped sinusoid from a speaker)

with the spectral peak of the stimulus at 1.4 kHz. Exposure levels ranged from 131 to 147 dB. Such impulses produced an approximate 30 percent loss of outer hair cells, with a total exposure energy of about 2 J per square meter. In dramatic contrast, Ward et al (1983) calculated that the energy required to produce a 30 percent loss of outer hair cells with their stimulus (a continuous exposure to a 700- to 2,800-Hz band of noise) would be about 22,500 J per square meter (as long as the levels were no greater than 114 dB). Similar results can be adduced with data from exposure of the cat ear. Miller et al (1963) found that exposure to a 115-dB continuous broad-band noise (spectral peak at 1.5 kHz) for 2 hours at about 2,200 J per square meter produced an average permanent threshold shift (PTS) of 38 dB. However, the rifle impulse, with a spectral peak in nearly the same region, but peak pressures of 145 to 155 dB, produced a similar loss with only 10 J per square meter (Price, 1986). Clearly, on the basis of data from the cat and chinchilla, there is reason to suspect that there is a significant difference in the response of the ear as a function of level.

On the basis of these arguments, we can conclude that the ear can become extremely fragile at high levels, and that a relatively small amount of energy can produce a large loss.

Opposing Functions

The title to this section might well be expanded to read: *"Opposing functions, or no wonder impulse noise data are so confusing."* The reader who has been paying careful attention should perhaps be confused at this point, given that arguments have just been developed one after the other that (1) because of nonlinearities in the middle ear, the ear should become *less* susceptible to intense sounds (it should take more energy to do damage); and (2) that because of a change in loss mechanism within the cochlea, the ear should become *more* susceptible at high levels, and a relatively small amount of energy could do a great deal of damage. Although the arguments appear to be contradictory, they are not, and in fact go a long way toward explaining both the unusual fragility and robustness of the ear.

The critical question posed in this chapter is whether a frequency domain analytical method is useful for dealing with what are essentially time domain questions, e.g., instantaneous, nonlinear displacements of structures. It seems unlikely at this juncture that spectral analysis will be useful at these very high levels.

Conclusion

The theoretical basis for the use of spectrum in rating hazard is well established for the sound intensities most often encountered in the workplace. The frequency-selective transmission characteristics of the conductive mechanisms of the external and middle ears, coupled with the generally broad and gently sloped spectra of noise in the workplace, promote energy transmission in the midrange so that some measure of energy there should do well at ranking hazard.

However, at sound pressure levels above 130 dB, the picture is much more complex. Important mechanisms come into play that can result in the ear becoming either very resistant or extremely susceptible to particular temporal patterns of stimulation. These mechanisms are not well characterized in the frequency domain; consequently, spectrum is likely to have only marginal utility in rating hazard for really intense sounds.

Importance de la Composition Spectrale des Bruits pour l'Estimation des Risques Lésionnels: Bases Théoriques

L'hypothèse du rôle important joué par le spectre dans l'évaluation du risque lié à l'exposition aux bruits intenses est admise de manière générale. Les bases théoriques des effets du spectre sont à rechercher dans divers aspects de la réponse de l'oreille aux bruits intenses. En premier lieu, la façon dont l'énergie est transmise du champ libre jusqu'à l'étrier conditionne celle qui atteint effectivement la cochlée, où se produisent la plupart des lésions associées aux pertes auditives. Il est maintenant bien établi, empiriquement et théoriquement, que l'oreille externe et moyenne agissent comme un filtre passe-bande, la meilleure transmission de l'énergie ayant lieu dans les fréquences moyennes.

Un facteur additionnel, qui se présente sur une base variable et qui peut jouer un rôle majeur, est constitué par l'atténuation pro-

duite par les muscles de l'oreille moyenne. Ces derniers peuvent provoquer une atténuation atteignant 40 dB aux basses fréquences, et un peu moins aux fréquences élevées, mais leur action est complexe. Des facteurs spectraux, temporels et même psychologiques conditionnent leur déclenchement, ainsi que leur importance et leurs effets.

Le risque est non seulement fonction de la susceptibilité du système, mais aussi des caractéristiques de la fonction excitatrice. Comme nous l'avons vu, l'oreille externe et moyenne constituent un filtre passe-bande étroitement accordé. Par ailleurs les bruits en milieu industriel tendent à avoir une distribution spectrale d'énergie large, avec des pentes comprises entre plus et moins 6 dB/oct. Par conséquent le filtrage dû à l'oreille externe et moyenne couplé à l'effet des muscles de l'oreille moyenne agit normalement de manière à produire à l'entrée de la cochlée, un pic spectral situé dans la gamme des fréquences moyennes.

A des niveaux dépassant 120-130 dB, nous pensons que l'oreille moyenne cesse d'être linéaire et qu'elle commence à écrêter, limitant ainsi les déplacements de l'étrier qui dépassent environ 20 microns (cette valeur étant quelque peu fonction de l'espèce). Par la limitation du déplacement, il se produit un décalage additionnel de l'énergie vers les fréquences élevées au niveau de l'entrée de la cochlée.

Finalement il reste la cochlée proprement dite, qui réalise une analyse spectrale du signal d'entrée entre sa base et son apex; ceci nous amène à nous intéresser à la susceptibilité des structures internes à la cochlée. A ce niveau, le raisonnement est beaucoup plus spéculatif. Cependant, on peut noter que les propriétés physiques de la membrane basilaire et de l'organe de Corti varient uniformément en fonction de sa longueur; l'existence de discontinuités dans sa susceptibilité est donc peu probable. Par ailleurs, la susceptibilité dépend du mécanisme spécifique lié aux pertes auditives. Par exemple, un calcul basé sur l'effet provoqué par l'énergie acoustique en un endroit donné, différera de celui basé sur la contrainte mécanique. Et, bien évidemment, les pertes cellulaires peuvent être reliées aux processus mécaniques de manière stochastique. Une analyse définitive du rôle du spectre est tributaire de l'acquisition d'informations nouvelles dans ce domaine.

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